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咸水安全利用农田调控技术措施研究进展*

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摘 要 淡水资源短缺已经成为全球性的问题，开发利用地下咸水资源，发展农业灌溉已成为各国关注的焦点问题。微咸水或咸水代替部分淡水进行农业灌溉，在一定程度上可缓解淡水资源的不足，但咸水和微咸水灌溉带来的土壤积盐和作物减产等问题始终是研究的重点和难点。本文从咸水或微咸水灌溉带来的潜在土壤盐渍化危害入手，就如何应对咸水和微咸水灌溉带来的次生盐渍化问题，通过总结前人大量的研究成果，分析了减轻土壤盐渍化对作物危害的各种途径，从微咸水灌溉和咸水灌溉两个层面就优化农田管理农艺措施、生物措施、水利工程措施等方面进行概述。重点介绍了咸水或微咸水灌溉对土壤微环境的影响，优化田间管理农业措施(如合理的灌溉制度和灌溉方式、覆盖、深耕等)，土壤中施入有机物质(如植物秸秆、有机肥、绿肥、生物质炭等)和无机土壤改良剂(如石膏、沸石等)、施用根际促生菌肥、种植盐土植物和耐盐作物品种等，以及咸水结冰灌溉、暗管排盐等水利工程措施，这些都是降低咸水灌溉带来的土壤盐害行之有效的方法。以微咸水或咸水补灌为核心，结合雨水资源利用，通过种植耐盐植物品种、增施土壤微生物肥、土壤调理剂等措施提高土壤缓冲能力，配套垄作和地膜覆盖等降低土壤蒸发措施，抑制土壤盐分表层积聚，配套秸秆还田和土壤耕作技术，提高土壤蓄雨淋盐和养分快速提升，集成微咸水安全高效灌溉技术模式，制定规范化的技术应用规程，有机地结合各种改良措施，可有效控制咸水和微咸水灌区土壤次生盐渍化，达到咸水资源的高效安全可持续利用，提升水资源保障能力。

关键词 微咸水灌溉 咸水灌溉 农田调控措施 生物措施 土壤环境 土壤次生盐渍化

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Advances in agricultural practices for attenuating salt stress under saline water irrigation*

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Abstract The shortage of freshwater resources has been a growing global concern. The use of saline groundwater and brackish water is an important way of solving water shortage in irrigated farmlands around the globe. Saline water and brackish water could partly replace freshwater in irrigated agriculture, but saline water or brackish water irrigation results in the accumulation of salts in surface soil and in the reduction of crop yield. This has been a significant research issue associated with water shortage and agricultural production in recent decades. In this study, measures developed to mitigate secondary salinization

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due to saline water irrigation were summarized. The measures included improving cultivation practices, biological practices and engineering designs that ameliorated soil salt stress under brackish water or saline water irrigation. The paper highlighted relevant current literatures and introduced detailed optimization agricultural cultivation manages, including the development of reasonable irrigation methods, mulching and subsoiling. There were also soil amendments with organic matter including crop residues, farm manure, green manure, gypsum, zeolite, etc. There was inoculation with plant growth promoting rhizobacteria, planting halophytes or salt-tolerance crop species, etc. All these measures were efficient in mitigating soil salt stress under saline water irrigation. In saline water and brackish water irrigation, the combination of rainfall with irrigation improved soil buffer capacity to salinity. Also planting salt tolerant crop cultivars and using biological fertilizers and soil conditioners could decrease soil salinity. Ridging and plastic mulching reduced evaporation loss while concurrently decreasing salt concentration in surface soil. Straw return to soil and deep tillage improved soil nutrient condition, water holding capacity and salt leaching. The integration of safe and efficient mode of saline water and brackish water irrigation, the designing of standard technology and application procedure, and the combination of various organic substances were all ameliorative measures. Field soil salt stress under saline water and brackish water irrigation was efficiently controllable. The effective, safe and sustainable use of brackish and saline water was achievable in improving water availability for agricultural production.

Keywords Brackish water irrigation; Saline water irrigation; Agricultural regulation practice; Biological practice; Soil environment; Secondary soil salinization

淡水资源短缺已经成为全球性的问题，特别是在干旱和半干旱地区。合理地开发利用地下咸水资源发展农业灌溉已成为各国关注的焦点问题。很多农业咸水灌溉研究结果表明，合理利用微咸水不会造成作物减产[1−5]。咸水灌溉是解决淡水资源严重缺乏的有效途径[6]。国内外利用咸水与微咸水进行农田灌溉已有近百年历史。我国从20世纪60、70年代就开始进行微咸水利用研究，在宁夏、甘肃、内蒙古、山西、河南、河北、山东等省区不同程度利用微咸水灌溉并获得高产。

浅层微咸水代替部分淡水进行农业灌溉，在一定程度上可缓解淡水资源的不足，但咸水灌溉带来的土壤积盐和作物减产等问题始终是研究的重点和难点。咸水灌溉会增加土壤的次生盐渍化风险[7]。土壤溶液中过量的盐，主要是钠盐，造成多种负面效应：主要有土壤结构稳定性的破坏，土壤水力学性质的恶化，作物产量的下降，微生物生物量和土壤酶活性的降低等[8−10]。不适宜的长期咸水灌溉导致土壤永久退化，破坏土壤生产力，造成严重的环境问题[11−12]。而土壤健康对于农业和环境的可持续发展至关重要，是作物生产的前提条件[13]。如果不采取任何改良措施，长期咸水灌溉将会导致作物产量显著下降[11]。因此，当务之急是研究出行之有效的管理措施以实现咸水灌溉条件下作物的高产和咸水的高效利用，最终达到资源和环境的协调可持续发展。关于如何消减咸水灌溉下土壤盐害问题，专家们已经尝试了很多方法，并取得了很多成功经验[14]。本文从咸水灌溉带来的潜在危害入手，就如何应对咸水灌溉带来的次生盐渍化问题，对咸水灌溉下农田调控技术措施进行了分析和总结，分别从微咸水灌溉($1\sim5\ g\cdot L^{-1}$)和咸水灌溉($>5\ g\cdot L^{-1}$)进行分析，希望对未来咸水或微咸水灌溉农业有一些指导意义。

1 咸水灌溉造成土壤微环境恶化

咸水灌溉快速改变了土壤溶液中的 Na^+、Ca^{2+} 和 Cl^-的浓度，土壤溶液中盐浓度取决于灌溉水含盐量和灌溉循环中所利用咸水的次数[11]。长期利用微咸水灌溉提高了土壤 pH 和交换性钠百分率(ESP)，破坏了土壤物理结构，导致作物产量下降[15−16]。在干旱半干旱地区，土壤蒸发大大超过了降水，地下水中盐分通过毛细管运动到土壤表层聚积。Na^+可以替代黏土矿物颗粒中的 Ca^{2+}和其他吸附在土壤表面或者在土壤团聚体间层中的 Mg^{2+}等土壤黏合剂，破坏土壤次生黏土矿物。随着灌溉水盐分含量的增加，土壤总孔隙度和土壤团聚体稳定性系数降低，土壤结构被破坏，土壤孔隙度下降，表层土壤容重和土壤饱和电导率增加，土壤水的渗透性降低，土壤的持水量增加[17]，导致土壤板结[18]。

咸水灌溉引起的土壤盐碱化问题不仅对土壤物理化学性质和作物生长造成很大负面影响，而且对土壤微生物的数量和活性以及维持土壤质量的生化过程都有很大影响[10]。土壤微生物是土壤团聚体形成和稳定的关键因素，土壤盐分的增加引起土壤微生物的呼吸作用和数量降低[19]，进而导致土壤团聚体分解，破坏土壤结构[10]。土壤中的Na^+主要是间接通过根系分泌物的数量或/和质量来影响根际土壤微生物结构，而不是对微生物产生直接的毒性[20]。

土壤养分有效性的降低也是盐碱土对作物产量的限制因素之一。微咸水灌溉明显抑制了土壤酶活

性, 造成了土壤微生物量和 CO_2 通量下降, 土壤有机物降解率降低, 使农田土壤生物性状变差[21]。高盐度咸水灌溉将会导致土壤有机质分解速度和土壤碳氮磷的矿化速度变缓, 从而降低土壤养分的有效性, 导致作物产量下降[22]。长期的微咸水灌溉降低了土壤有机碳和总氮含量[23]。灌溉电导率小于 4.61 $dS\cdot m^{-1}$ 的微咸水对棉花生长和水氮利用效率没有影响, 而利用电导率大于 8 $dS\cdot m^{-1}$ 的咸水滴灌时则抑制棉花生长, 降低水氮利用效率[24]。劣质灌溉水中的 Na^+、Ca^{2+}和 Mg^{2+}参与了土壤离子交换过程, 导致土壤云母矿物中 K^+被置换出来, 并被淋洗到溶液中, 从而提高地下水的 K^+浓度。咸水灌溉条件下, 特别是 Mg^{2+}含量较高的水灌溉时, 会增加土壤中 K^+的释放, 更利于作物吸收, 但是长远来看这些钾会被淋洗到根层以下[25–26]。如果没有足够的钾肥投入, 长期咸水灌溉会导致作物产量下降[27]。在沙壤土上咸水灌溉会造成土壤 Ca^{2+}、Mg^{2+}、K^+和磷的淋洗, 同时增加浅层地下水盐度增加的风险[28]。

2　微咸水灌溉条件下农田调控措施

2.1　优化田间管理农艺措施

田间管理农艺措施主要是物理的改良措施, 是对咸灌土壤改良最直接的方法, 主要包括优化灌溉方式和灌溉制度(如选用滴灌节水灌溉方式, 利用灌水洗盐, 轮灌或混灌, 优化咸淡水的灌溉次序等), 深耕、深松、翻土、无机物(塑料薄膜)和有机物(作物秸秆等材料)覆盖等方法。

2.1.1　优化灌溉制度

从微咸水的灌溉方式来看, 主要有漫灌、沟灌、喷灌和滴灌。漫灌和沟灌灌水定额大。从节水角度讲, 喷滴灌具有明显优势。滴灌技术引入到微咸水利用中称之为微咸水灌溉的一次革新。滴灌利用微咸水主要有两方面优势: 一是避免了叶面损伤, 二是由于滴灌的淋洗作用, 盐分向湿润锋附近积累, 因此在滴头下面的土壤含盐量比较小, 有利于作物生长, 并且维持一个高的基质势, 同时在滴灌条件下土壤水分含量分布与盐分分布正好相反, 有利于作物根系发育生长和水分养分的吸收利用[29]。与沟灌相比, 滴灌保持了理想的土壤水分含量, 减少了根区的盐分含量, 同时土壤物理性质和养分状况都有明显改善, 土壤微生物量和土壤酶活性增强, 在滴灌条件下水分利用效率比沟灌平均高1/3, 有利于在不降低产量的前提下高效利用微咸水资源从而缓解淡水资源严重缺乏的问题[30]。

将覆盖和滴灌相结合的微咸水膜下滴灌模式为干旱半干旱地区有效利用微咸水资源以及盐碱地的开发利用提供了参考。膜下滴灌既具备滴灌的防止深层渗漏、减少棵间蒸发、节水、节肥的特点, 同时还具备地膜栽培技术的增温、保墒作用, 滴灌在根区可以形成淡化的脱盐区, 覆膜抑制了膜内的土壤蒸发作用, 并使膜内盐分发生侧向运移, 同时减少深层渗漏, 降低了次生盐渍化发生的可能性, 因此膜下滴灌也被用于防治土壤次生盐碱化。与传统的表面滴灌相比, 采用地下滴灌的方式进行微咸水灌溉对防止盐分在耕层土壤的表聚有良好效果, 已经被广泛应用在淡水资源缺乏的干旱半干旱地区[31–32]。长期滴灌下土壤盐分积累特征是决定这一灌溉方式能否可持续的重要问题。膜下滴灌的咸淡水轮灌时序对作物产量和土壤积盐状况也有很大影响[33]。但利用膜下滴灌方式进行微咸水灌溉, 目前仍存在一些问题, 需要进一步研究[34–35]。

咸水灌溉的技术关键是如何使土壤积盐不超过作物耐盐度, 因此, 需要通过试验研究制定合理的咸水灌溉制度, 包括咸水灌溉量、灌溉次数、灌溉时期、灌溉水盐分浓度等。优化灌溉方式结合根层土壤盐分管理需要考虑蒸散、盐分含量、土壤类型、降水、地下水位、作物类型和水分管理的交互作用, 针对微咸水或者咸水灌溉土壤盐分积累规律来因地制宜地制定合理的灌溉制度。目前, 咸淡水混灌轮灌已被广泛利用。该技术不仅可以实现微咸水资源充分高效利用, 同时能较好地控制根层盐分表聚, 保持作物根层水盐平衡并保障作物生产安全。作物不同生育时期对水分和盐胁迫表现不同。可因地制宜地制定后期漫灌措施, 以便淋洗土壤中积累的盐分。作物收获后一次大的漫灌可有效减少土壤中盐分的累积, 该措施比在生育期灌溉同样量的水在土壤控盐方面更有效[36]。由于淡水资源的匮乏, 淋盐排盐措施在有条件的地区才能进行。

2.1.2　覆盖和深松耕作措施

表层土壤中盐分的累积可以通过减小土壤蒸发来控制。与裸地相比, 塑料薄膜覆盖, 特别是作物秸秆覆盖减少了土壤水蒸发损失, 对控制盐分积累更有效[37]。秸秆覆盖可以降低微咸水灌溉所导致的表层土壤的盐分累积和土壤钠吸附比增加[38–39], 与此同时还能够改善盐分在土体中的垂直分布, 使土壤根系分布密集层保持较低盐分水平, 缓解盐分对作物的危害, 并有显著的增产效果[40–41]。

深松和秸秆覆盖处理降低了 0~30 cm 土层的土壤容重, 增加了土壤孔隙度, 改善了土壤水溶性团聚体的分布。与传统耕地和秸秆移除处理相比, 由

于土壤结构和渗透性得到改善，深松和秸秆覆盖使得土壤含盐量降低了20.3%~73.4%[42]。

2.1.3 起垄措施

起垄人为造成微域地形的高差，导致地表的不均衡蒸发，低处水盐向高处移动。起垄措施产生的土壤微地形变化改变了局部土壤水、盐的空间分布，同时改善了土壤物理状况，使垄沟内土壤理化状况优化。垄作下沟灌方式较常规畦灌对于降低土壤盐分具有更好的效果，沟灌玉米根系较发达，灌溉水利用效率高，综合考虑沟灌是低水分条件下一种较好的灌溉方式[43]。起垄覆膜种植方法，是集农田微域集水和地膜覆盖两大旱作栽培方法优点于一体的作物栽培新技术，依据农田微工程覆膜雨水富集叠加、雨水就地入渗、覆盖抑蒸三大理论，把"膜面集雨、覆盖抑蒸、垄上种植"三大技术相互融合为一体，具有明显的改善地温和土壤物理性状、培肥改善地力的作用[44]。与起垄不覆膜土壤盐分的分布有所不同，起垄覆盖相结合的方法使沟底部含盐量高于垄下土壤含盐量，作物种在垄上有助于微咸水灌溉下作物避开土壤积盐对作物的影响[45]。

2.1.4 施用土壤改良剂

盐碱化土壤最有效的改良方法是根据可溶性钠盐的去除和交换，通过添加化学物质改变土壤的离子构成，同时把Na^+淋出到土壤剖面以外。几种降低咸水灌溉下盐害的方法已经被推荐使用。这些方法包括施用石膏或者氯化钙、沸石等无机的土壤改良剂降低咸水灌溉条件下土壤中Na^+的置换。考虑到在土壤中施入化学物质的成本和对环境的影响，寻找更廉价的天然改良剂更有意义。在土壤中添加有机物质如植物秸秆、有机肥、绿肥、动物粪便、泥炭、褐煤粉和生物炭都是降低咸水灌溉下土壤盐害行之有效的方法。

1)有机改良剂

添加有机物质可以加速钠的淋洗，降低ESP和电导率，增加土壤持水能力和土壤团聚体的稳定性[8,46]。另外，Walker和Bernal[47]的研究结果表明有机添加物可以增加阳离子交换量，土壤交换点首先被Ca^{2+}、Mg^{2+}和K^+占据从而阻止Na^+进入交换点。长期定位试验结果表明，在小麦–水稻轮作微咸水灌溉区，单独填加有机物质如小麦秸秆、绿肥、农家堆肥等可以溶解石灰性土壤中内在的Ca^{2+}和$CaCO_3$沉淀中的Ca^{2+}，增加了土壤渗透速率，从而获得稳定的产量[16]。施用畜禽粪便，农家粪肥在提高土壤肥力的同时，降低了土壤电导率和pH，可以防治微咸水灌溉造成的土壤次生盐渍化，缓解了微咸水灌溉对作物的危害[48–49]。施用腐殖质可以增加土壤的持水能力和养分保持能力，保持良好的土壤结构和高的微生物活性，腐植酸可以显著减少土壤水的蒸发，提高水的作物有效性。另外，腐殖质促进了多种矿质元素在土壤中转化成作物利用的形式[50–51]。施用腐殖质是消减咸水灌溉带来的土壤盐害的有效措施之一。

增施有机肥料不仅能增加土壤中腐殖质含量，有利于土壤团粒结构的形成，还能改善盐碱土的通气、透水和养分状况。在盐碱土上氮的释放在很大程度上取决于有机填加物的可溶碳和总氮的比值[52]。秸秆添加大大增加了土壤氮磷的有效性。在盐害条件下，微生物碳氮磷显著受到土壤质地和秸秆填加物的影响[53]。虽然随着土壤盐分的增加土壤微生物的呼吸作用和生物量降低，但是填加秸秆后则增加了土壤微生物的呼吸和生物量，且沙壤土高于黏土，苜蓿秸秆优于小麦秸秆[53]。秸秆还田后的土壤耕层结构疏松，容重降低，非毛管孔隙度显著增加，能有效抑制土壤盐分表聚，使作物主要根系活动层保持较低盐分水平而不影响作物正常生长[54]。增加葡萄糖提高了盐土微生物的活性和生长，减轻了土壤盐分对微生物的负面影响[19]。因此，添加有机物质增加了碳源，在一定程度上缓解了咸水灌溉造成的对土壤微生物和养分有效性的影响，提高了土壤质量。

近年来由于国内很多地区农业实现了机械化，秸秆还田被大面积推广应用。土壤中深埋的秸秆层起到了水和盐分上移的障碍层，阻止了深层土壤和浅层地下水盐分上移，抑制了耕层土壤返盐。利用作物秸秆和牛粪填满到土壤里，结合薄膜覆盖和滴灌技术做成生物反应器应用到大棚蔬菜种植中，对于消减咸水灌溉带来的土壤盐害有良好的使用效果[55]。生物反应器既降低了土壤盐分浓度，又提高了土壤有机质和养分含量，改善了土壤环境，提高了作物产量和品质[55]。

在旱地上良好的水分管理配以合理的土壤管理措施是作物生产可持续发展的必要条件。有机填加物含有大量的养分，它们可以释放到土壤中供作物吸收利用。但是如果用含有高浓度的Na^+和Ca^{2+}的微咸水灌溉时会导致养分淋洗出根区土壤。因此微咸水灌溉添加有机物质时必须配套阻止养分流失的相关技术[48]。另外，有些研究表明施用动物粪便，例如，家禽粪便[56]和猪粪堆肥[57]会导致土壤盐分增加，加重了咸水灌溉下土壤盐害对作物的影响，所以在对盐分敏感的土壤上应该慎重施用有机肥。

生物质炭(biochar)是近年来关注较多的新型土壤改良剂。生物质炭是指动植物残体或其他生物质在完全或部分缺氧的情况下，以相对“低温”(<700 ℃)热解炭化，产生的一类高度芳香化难熔性固态高聚产物[58]。施用生物炭可以使作物产量平均提高 11%左右[59]。生物质炭可以改变土壤的物理化学性质，提高土壤肥力，同时可以预防土壤的生物化学性质退化[60]。利用其高吸附性的特点，在盐碱土上施用生物质炭可以降低土壤容重，改善土壤通气状况，增加阳离子交换量，明显改善土壤的物理化学性质[61−62]，降低土壤盐含量、钠吸附比(SAR)和 ESP[63]，同时增强盐碱土壤碳的固定，减少温室气体排放，提高作物产量[64]。微咸水灌溉下施用生物炭促进了马铃薯的生长，降低了茎基部伤流液和叶片的脱落酸(ABA)含量，提高了茎基部伤流液中 K^+/Na^+比值，降低咸水灌溉下土壤积盐对马铃薯的危害[65]。微咸水灌溉下，施用生物炭可以减少土壤中可溶性铅(Pb)含量，降低玉米对铅的吸收从而提高作物品质[66]。

2)无机改良剂

在微咸水灌溉下加入石膏[23]、沸石[67]等无机土壤改良剂缓解土壤盐渍化方面已经做了大量研究。咸水灌溉下添加石膏可以明显改善土壤的物理化学特性，可以使水稻产量提高 12.5%，小麦产量提高50%[16]。长期微咸水灌溉增加了土壤 pH、SAR 和ESP，降低了土壤有机碳和总氮，而施入石膏和有机添加物(如绿肥、农家堆肥和水稻秸秆)都改善了这些土壤性质[23]。微咸水灌溉对土壤的盐渍化危害因土壤有机质含量不同而不相同[68]，经过土壤添加硫酸钙和淋洗措施后土壤结构有不同的改良效果，有机质含量高的土壤土壤孔隙度不受灌溉水盐分的影响，而有机质含量低的土壤咸水灌溉后孔隙度则变小，这可能因为土壤中铁铝氧化物的含量不同，从而造成土壤团聚体稳定性不同的缘故[18]。微咸水灌溉条件下添加石膏和农家堆肥还提高了土壤氮的矿化[23]。如果利用咸淡水轮灌或者添加合适的土壤改良剂等措施，微咸水灌溉对小麦−棉花轮作区作物产量和土壤质量没有负面影响[69]。在缺乏淡水资源无法实现咸淡水轮灌的情况下，如果用含有高量钠离子的水进行灌溉必须使用石膏[69−70]。

2.2　生物措施

2.2.1　施用微生物肥料

在淡水或者有限淡水灌溉条件下，高氮肥施用量可以获得更高的产量。而在微咸水灌溉条件下，在充足或者亏缺灌溉下，低氮肥施用量获得最佳产量[71]。微咸水灌溉条件下过多的氮肥投入会加重对作物的盐害[24]。若没有其他胁迫，微咸水灌溉条件下作物需要较少的氮肥用量[72]。而微生物肥料一般具有无机养分含量比较低的特点，微生物肥料可以代替23%~52%的氮肥而不减少产量，但是并不能代替磷肥[73]。施用根际促生菌肥(plant-growth-promoting rhizobacteria, PGPR)已证明是一种促进小麦在盐碱地生长的重要措施。根际促生菌具有成本低，易操作和对土壤无副作用等优点。接种根际促生菌是在盐害条件下促进作物生长和最大化利用盐碱土的有效方法之一[74]。

微生物肥料的施用替代了部分化肥，提高了化肥利用率。近年来研制应用的具有土壤调理等新型功能的微生物肥料，在提升耕地土壤环境质量上意义重大[75]。微生物群体对土壤团聚体的稳定性起着至关重要的作用[76]。在干旱半干旱地区，土壤团聚体的稳定性是促进作物生长和防治水土流失的一个重要性质。因此，在退化的盐碱土农业体系中改善土壤团聚体的性质显得尤为重要。微生物肥料具有其他肥料无法比拟的优点，具有多重功效，在提升咸水灌溉下土壤盐害缓冲能力方面具有明显的优势。

菌根真菌可以显著地降低植物对 Na^+和 Cl^-的吸收，同时促进园艺作物对钾和磷的吸收。接种菌根真菌是一种合适的可以提高中高盐度微咸水灌溉时园艺作物抗盐性的的方法[77]。接种丛枝菌根真菌可以改善土壤结构，提高土壤有机碳和土壤速效养分含量[78]。此外，丛枝菌根真菌提高了盐害条件下作物的光合作用和水分利用效率[79]。菌根真菌可以改善作物的碳氮代谢过程，提高其相对含水量、膜的稳定性和叶片光合速率，促进蛋白的合成和渗透调节物质的累积，改善作物的营养状况等，从而降低了土壤盐害对作物产量的影响[80]。

利用固氮根际促生菌可以促进玉米对 K^+的吸收，排斥对 Na^+的吸收，增加 K^+/Na^+比值，同时提高叶片叶绿素含量，从而增强玉米的抗盐性。施用固氮根际促生菌是一种降低作物盐害的重要生物方法[81]。根际促生菌在田间显著促进小麦的生长并提高其产量[82]。根际促生菌接种的小麦体内具有低钠含量和高氮磷钾含量[74]。根际促生菌促进了植物根际养分的循环[83]，增强了作物吸收养分能力，在维持小麦体内养分平衡方面起着重要作用。无论在盐还是非盐害条件下，根际促生菌主要通过直接或者间接调控植物的叶绿素含量、叶片的渗透势和细胞膜的稳定性和离子的积累等[84]，促进了白三叶草的生长。

尽管根际促生菌作为降低盐害对作物影响的新兴技术具有非常多的优点，但微生物肥料也有不足

之处：在控制条件下(实验室或者温室)根际微生物对作物生长具有促进作用，但是在田间由于自然条件变化，PGPR的效果具有不确定性。由于根际促生菌不会永远在土壤中存活，在田间必须每年或者每季重新接种[85]，这促使我们筛选分离出更先进的菌种。这些菌种时而有效时而无效，其原因是根际促生菌的群体大小和活性受到土壤环境条件的影响[86]。根际促生菌的使用效果取决于水的盐浓度和寄主作物的生长阶段[87]。45%生物肥料的施用效果取决于作物氮磷钾肥的施用量和施用时间[73]。农民和农学家需要认识到化肥和微生物肥料的双重管理才能实现微生物肥料的成功应用。

2.2.2 植物改良技术

种植盐土植物是盐碱地脱盐的一条重要途径。田间和温室试验结果表明种植盐土植物使得土壤电导率显著下降，碱蓬可以移除氯化钠 1~6 $t \cdot hm^{-2} \cdot a^{-1}$[88]。这些结果与微咸水灌溉条件下根据干物质中 Na^+和Cl^-浓度和总的生物量来计算的 NaCl 移除量是一致的[88]。种植绿肥作物如田菁等可以改善微咸水灌溉下土壤的物理化学性质，提高小麦和水稻产量，尤其是石膏和种植绿肥配合改良效果最佳[89]。另外，种植转基因的耐盐植物可以提高产量[90–91]。

与土体土壤相比，盐碱土根际土壤具有低含盐量、高水分含量和较高的土壤微生物数量。丰富的根际土壤微生物表明根系可以降低土壤盐害并提供有利于微生物生存的环境。植物根际土壤总的微生物丰度和多样性提高了微生物维持退化土壤系统正常运行的能力[92]。土壤中的 Na^+主要是间接通过根系分泌物的数量或/和质量来影响根际土壤微生物结构，而不是对微生物有直接毒性[20]。根系分泌物与地上部[93]和根系[94]的生物量呈正比。寄主植物的耐盐能力决定了在高盐条件下能否成功组成根瘤菌–大豆共生体系[95]。植物的健康程度是根际微生物结构和氮循环的主要决定因素[53]。种植耐盐作物间接改善了咸水灌溉条件下土壤的微生物结构和养分状况，提升了咸灌土壤盐害缓冲能力。作物各个品种之间耐盐性差异较大，微咸水灌溉下种植耐盐性较好的作物品种直接影响到其最终产量[96]。

除上述农田调控措施以外，微咸水结冰灌溉能够有效控制耕层土壤微咸水灌溉下的盐分累积，与秸秆覆盖措施配合效果更明显[97]。

3 高矿度咸水灌溉下农田调控措施

国内外关于咸水灌溉对土壤、水分、盐分和作物的关系研究较多，但大多研究矿化度为 2~5 $g \cdot L^{-1}$的微咸水，而对于矿化度大于 5 $g \cdot L^{-1}$的高矿度咸水许多研究都指出难以利用或应慎重利用。高矿度咸水会对作物的生长造成很大影响，叶片净光合速率下降[98]，耕层土壤盐分累积[38]，加速土壤氮素淋洗，氮肥利用率降低[99]，土壤退化，造成作物减产[38,98]。

高矿度咸水不能直接用于灌溉，大多通过混灌的方式配成微咸水进行灌溉[45]。由于极度缺乏淡水，以色列通过反渗透等技术将咸水淡化后用于灌溉，由于淡化后缺少作物生长所必须的钙镁硫等元素，采用淡化水和咸水混灌的形式取得良好的效果[100]。与淡水灌溉相比，高矿度咸水采用膜下滴灌的方式对马铃薯进行灌溉并没有造成减产[32]。咸水灌溉可以作为一种抗干旱应急措施用在淡水严重缺乏盐碱地区的耐盐作物上(如棉花等)，但是咸水灌溉后，必须利用淋洗和排水等措施保持表层土壤脱盐才能实现农业可持续发展和粮食安全[101]。

咸水(16 $dS \cdot m^{-1}$)灌溉显著抑制了大麦生长，而添加土壤改良剂沸石以后大大促进了大麦的生长，这是因为添加沸石降低了土壤特别是表层土壤的 Na^+、Mg^{2+}和 Ca^{2+}浓度[67]。覆盖措施能够改善高矿化度咸水灌溉下盐分在土体中的垂直分布，抑制土体盐分上移，防止盐分表聚现象的发生，且比微咸水灌溉条件下对土壤的削减作用更明显[38–39]。

冬季咸水结冰灌溉技术，即冬季利用当地地下咸水灌溉盐碱地，在低温作用下，咸水形成冰层，由于不同含盐量咸水的冰点不同，融化时先融化的高含盐量咸水先入渗，后融化的微咸水和淡水入渗对土壤盐分具有淋洗作用[102–103]，可促进表层土壤的脱盐作用，淋洗主要危害性离子Na^+和Cl^-等，保持土壤根系分布密集层较低盐分水平和盐基离子平衡，缓解或消除盐分和盐基离子对作物生长的危害[97]。咸水结冰灌溉技术必须配合秸秆覆盖技术效果更加明显，如果不配以覆盖措施或者覆盖较晚，咸水结冰灌溉也得不到理想的控盐效果[104]。

暗管排盐技术是目前治理盐碱地比较成熟的技术，其主要原理是根据“盐随水来，盐随水去”的水盐运移原理，在有降水或灌溉发生时，盐随水下移至暗管处，通过暗管排除土体达到淋盐洗盐的效果，同时通过暗管将地下水位控制在临界深度，有效抑制高矿化度水的上移，减轻土壤次生盐渍化[105]。暗管排盐技术在咸灌土壤防治次生盐渍化方面有着显著效果，尤其是滨海低平原地区有着广阔的适用空间，该技术的应用使滨海盐碱地区可利用耕地面积扩大，区域生态服务功能得到提升[106–107]。

4 结论

目前人们在生产实践中认识到，防治土壤次生盐渍化采取任何单一措施的效果均有限，且不稳定。选用单一的改良措施进行改良，可能存在效果不全面或有不同程度的负面影响等不足之处。各国在应用改良措施时，趋于强调综合改良措施。将不同改良措施配合施用，特别是生物改良剂与工农业废弃物的配合施用近年来引起较多关注。多种改良物质的混合物结合培肥对咸水灌溉土壤进行改良，可缓解咸水灌溉土壤结构性差、肥力低的问题，真正实现土地的可持续利用和保护[108]。例如生物有机肥即有益微生物菌群与有机肥结合形成新型、高效、安全的微生物有机肥料[109]。

我们要以微咸水或咸水补灌为核心，结合雨水资源利用，通过种植耐盐植物品种、秸秆还田减蒸抑盐、增施土壤微生物肥、土壤调理剂等措施提高土壤缓冲能力，降低盐分对作物的危害；配套垄作和地膜覆盖等降低土壤蒸发措施，抑制土壤盐分表层积聚，配套秸秆还田和土壤耕作技术，提高土壤蓄雨淋盐和养分快速提升，降低盐害；集成微咸水安全高效灌溉技术模式，制定规范化的技术应用规程，并对示范效果进行充分评价，有机地结合各种改良措施(如化学改良、耕作改良、秸秆覆盖等)，有效地控制咸水灌区土壤次生盐渍化，达到咸水资源的高效安全可持续利用，提升水资源保障能力。

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